

NOCTURNAL SURFACE-SOIL TEMPERATURES, AIR TEMPERATURES, AND GROUND INVERSIONS IN SOUTHERN ARIZONA

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[Desert Laboratory, Carnegie Institution of Washington, Tucson, Ariz., February 1937]

The frequency and magnitude of nocturnal temperature inversions in the Southwest, especially in the dry and warm Sonoran Desert, have been discussed by MacDougall,¹ Shreve,² and Douglass.³ MacDougall and Shreve have pointed out the significance of "cold air drainage" for the distribution of plants in the region. Douglass has described an optical device which can be used to observe air currents at night, and had recorded some of his observations of these currents.

Thermograph traces from the Desert Laboratory, Tucson, Ariz., indicate that during 1936 two-thirds of the nights there had a pronounced ground inversion. Tucson is located in the Santa Cruz River basin at an elevation of 2,300 feet. Ten miles west the Tucson Mountains rise to an elevation slightly over 4,000 feet; 15 miles north are the Catalina Mountains (9,000 feet); 20 miles east are the Rincon Mountains (8,000 feet); and 40 miles south are the Santa Rita Mountains (9,000 feet). Below 6,000 feet the vegetation is a subtropical desert type while that of the higher elevations is coniferous forest. The Desert Laboratory is located on the north slope of Tumamoc Hill, 1 mile west of Tucson and of the usually dry bed of the Santa Cruz River, and is 330 feet above the flood plain. Tumamoc Hill rises 750 feet above the plain.

A thermograph at the laboratory and another on the flood plain near the base of the Hill, both in shelters 5 feet above the ground, are in continuous operation. The difference between the minimum readings of the two has been used as a crude index of the magnitude of the inversion each night. Recent readings on the summit of Tumamoc Hill indicate that the inversion, on nights when well developed, may extend to the hill top. The normal difference between the flood plain and Laboratory stations on inversion nights of 1936 was 9° F. although differences of 15° F. were not unusual and one of 23° F. occurred. During the summer rainy season inversions are usually

lacking or poorly developed. The dry months of April and May have the most pronounced inversions, as do the dry periods of winter. Over the town a smoke haze develops under these inversions, but over the scantily populated basins of the region I have observed little haze under the inversions. Dew deposition on the ground during an inversion is uncommon. High cirrus clouds and winds less than 6 miles per hour do not seem to alter materially the difference in minimum temperatures between the laboratory and flood plain stations.

Typical data selected from a large number of observations are presented in the accompanying table. The readings, unless noted otherwise, were obtained with a thermocouple (no. 24 advance—copper wires) and a portable type Leeds and Northrup galvanometer. As the coldest air was found immediately above the ground, the air temperature at the height of 1 inch is used throughout the table. Temperatures of the surface soil underlying the observed air layers are listed, care having been taken in the measurements to eliminate the influence of the observer's body. The observations were made on soil locally free of vegetation and with unobstructed vista of the sky. Readings with mercurial thermometers for the surface soil were made by inserting the bulbs as shallowly as possible into the soil; and for the air the bulbs were openly exposed. Experience has shown that the minimum temperature of the soil surface is obtained rather more accurately than that of the air. Each group of readings represents one night. On each night, except that of group I, there was a well-developed inversion.

¹ MacDougall, D. T.: Influence of Inversions of Temperature, Ascending and Descending Currents of Air, upon Distribution, Boston, 1900.

² Shreve, Forrest: Cold Air Drainage, *Plant World*, 1912; Winter Temperatures and Distribution of Plants, *Am. Jour. Botany*, 1914.

³ Douglass, A. E.: Study of Atmospheric Currents by Aid of Large Telescopes, and the Effects of Such Currents on the Quality of the Seeing, *American Meteorological Journal*, March 1895; Atmosphere, Telescope, and Observer, *Popular Astronomy*, June, 1897; Effect of Mountains on Quality of the Atmosphere, *Popular Astronomy*, 1899.

Group	Station	Elevation	Date	Time	Sky	Soil	Air at 1 in.	Temperature of surface (°F.)		
								Soil	Snow	Rock
I	Santa Cruz Basin	Feet 2,330	Dec. 28, 1936	10 p. m.	Cl-St; overcast, turbulent.	Moist clay	°F. 52.8	51.3		
II	Santa Cruz Basin	2,330	Jan. 5, 1937	10 p. m.	Clear; calm	Moist clay	32.0	32.5		
	do	2,330	Jan. 6, 1937	8 a. m.	do	do	28.6	29.1		
	Tumamoc hill slope	2,660	Jan. 6, 1937	Minimum	do	do	31.2	30.2		
III	Santa Cruz Basin	2,330	Dec. 1, 1936	10 p. m.	do	do	36.9	37.4		
	do	2,330	Dec. 2, 1936	8 a. m.	do	do	27.4	29.8		
	do	2,330	Dec. 2, 1936	Minimum	do	do	24.6			
	Tumamoc hill slope	2,660	Dec. 2, 1936	do	do	do	24.6	28.4		
IV	Catalina Mountain canyon	7,650	Nov. 17, 1936	6 p. m.	Clear; light breeze	Dry sand	37.4	37.7		
	do	7,650	Nov. 17, 1936	12 p. m.	do	do	30.6	32.0		
	do	7,650	Nov. 18, 1936	6 a. m.	do	do	27.9	29.3		
	Tumamoc hill slope	2,660	Nov. 18, 1936	Minimum	Clear; calm	Dry clay	37.1	41.0		
	Santa Cruz Basin	2,330	Nov. 18, 1936	do	do	do	33.8			
V	Baboquivari Peak	7,860	Dec. 12, 1936	9 p. m.	Clear; windy	Wet sand; rock	34.1	30.9	26.4	
	do	7,860	Dec. 13, 1936	8 a. m.	do	do	32.7	30.5	26.4	
	Baboquivari Basin	3,500	Dec. 13, 1936	Minimum	Clear	Dry sand	30.2			34.5
VI	Tucson Mountain ridge	3,200	Jan. 28, 1937	10 p. m.	Thin Cl; calm	Dry sand	43.7	41.5		
	Tucson Mountain arroyo	2,500	Jan. 28, 1937	10:30 p. m.	do	do	37.4	37.9		
	Santa Cruz Basin	2,330	Jan. 28, 1937	9 p. m.	do	Dry clay	32.0			

¹ Denotes mercurial thermometer readings.

NOTE.—Baboquivari Peak is about 40 miles southwest of the Santa Cruz Basin.

Observations of this type—made intermittently during the night and at one or only a few stations—can be misleading. Fitful breezes may import warmer or colder air to the vicinity of the instrument shortly before an observation is taken. Stations may be poorly selected in spite of efforts to find representative or extreme conditions. The “cold air drainage” may actually have its source in none of the locations where measurements are taken. More stations and more nearly continuous observations are desirable. Nevertheless, certain tentative conclusions are suggested by the data.

Group I presents a condition not uncommon on cloudy and windy nights—the surface of the basin soil cooling to a lower temperature than the air overlying it. Group II shows relations on an inversion night—the coldest air in the basin having a temperature lower than that of the basin soil and of the hill-slope soil and air. The air on the hill slope is the thin layer of cold air near the soil which on this particular night was 10° F. colder than the air 5 feet above the ground. The difference in the basin between these two heights is much less, being on this night 4° F.

Readings in a mountain canyon are given in group IV. The drainage of cold air down the canyon was easily detected, this air being colder than the soil of the canyon.

This air, however, was not cold enough to reach the basin gravitationally unless it underwent considerably more cooling during its descent. Observations on other nights at lower elevations (group VI) did not reveal any stream of air sufficiently cold to reach the basin gravitationally. If this stream of air at high elevations does cool sufficiently on its journey to descend to the basin, it must have overcome the adiabatic warming of approximately 5.5° F. per 1,000 feet of descent.

The greatest observed difference between nocturnal soil and air temperatures (with the former the colder) are given in group V, the station being a high, isolated peak. Snow on the peak was considerably colder than both air and soil; the soil was frozen to a depth of several inches. Bare rock nearby, however, was warmer than the air. On the same peak, when there was no snow present, as on the night of January 20, 1936, the air became ½° F. colder than the soil; but on the night of May 16, 1936, the soil became 3° F. colder than the air.

At midday in the shade of a cliff at 4,000 feet elevation, moist soil has been observed to be 12.5° F. colder than the air. Beneath the surface this soil was frozen, perhaps the result of low temperatures the previous week. However, snow and frozen soil on the mountains are rare during the season of greatest basin-inversions.

THE GEOMETRICAL THEORY OF HALOS—IV

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PART 2. CALCULATION OF POSITIONS OF IMAGES ON THE CELESTIAL SPHERE

From the general Formulae I, II, or III (or the appropriate special case of some one of these) the position of any image, *relative to the source*, produced by prismatic refraction, simple reflection, or prismatic refraction in combination with an internal reflection, may always readily be computed. These formulae will now be applied to derive formulae for the position *relative to the horizon* when the source is the sun or the moon at a given altitude; the derivation is essentially a transformation from spherical coordinates relative to the principal plane, or the reflecting plane, to the familiar horizon coordinate system of astronomy (with azimuths measured from the vertical circle through the sun).

IMAGES PRODUCED BY PRISMATIC REFRACTION WITHOUT INTERNAL REFLECTION

The derivation of the desired formulae may be accomplished by superimposing figures 5, 7, 11 in the proper orientation on the celestial sphere.¹ Figure 5 is the one required in the case of prismatic refraction without internal reflection.

Images produced by a dihedral angle with vertical refracting edge (principal plane horizontal).—Place figure 5 on the celestial sphere as in figure 12, with P' at the zenith Z , the great circle PRP on the horizon EME , and S in the position of the sun or the moon at altitude H above the horizon.

Then evidently $h=H$; and to compute the altitude H' , the azimuth ζ from the solar vertical, the deviation D , and the position angle A' (measured from above the luminary) of the image S' , at any given value of H , we have immediately from Formulae I the equations that comprise Formulae A. (It is of course unnecessary to

make any actual use of equation (1) in the calculation if table 3 is used.)

FORMULAE A

CALCULATION OF THE IMAGE PRODUCED BY A DIHEDRAL REFRACTING ANGLE WITH VERTICAL REFRACTING EDGE

Parameter: $H, 0^\circ \leq H \leq \arccos \left[\sqrt{\mu^2 - 1} \tan \frac{\alpha}{2} \right]$

Argument: i_1

Calculation of D, A', H', ζ :

$$(1) \mu' = \sqrt{\frac{\mu^2 - \sin^2 H}{1 - \sin^2 H}} \quad \text{Table 2}$$

$$(2) \sin r_1 = \frac{\sin i_1}{\mu'},$$

$$\arcsin \left\{ \sin \alpha \sqrt{\mu'^2 - 1} - \cos \alpha \right\} \leq i_1 \leq 90^\circ \quad \text{Table 3}$$

$$(3) r_1' = \alpha - r_1$$

$$(4) \sin i_1' = \mu' \sin r_1'$$

$$(5) D' = i_1 + i_1' - \alpha \quad \text{Table 3}$$

$$(6) \begin{cases} D = 2 \arcsin \left\{ \sin \frac{1}{2} D' \cos H \right\}, & D < D' \\ D_o' = 2 \arcsin \left\{ \mu' \sin \frac{\alpha}{2} \right\} - \alpha \\ D_m' = 180^\circ - \left\{ \alpha + \arccos \left[\mu' \sin \left(\alpha - \arcsin \frac{1}{\mu'} \right) \right] \right\} \\ A' = \arccot \left\{ \tan \frac{1}{2} D' \sin H \right\} \end{cases}$$

$$(7) \begin{cases} H' = H \\ \zeta = D' \end{cases}$$

[See figure 12. These formulae are obtained by putting $h=H$ in Formulae I.]

Images produced by a dihedral angle with horizontal refracting edge (principal plane vertical).—To compute the image produced, at any altitude of the sun or moon, when

¹ These figures appear in Papers II, III. The figures in the present paper are numbered consecutively with those in the preceding two papers.